

Puzzles in Cabibbo-Suppressed Charm Decays

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Abstract

We identify two Cabibbo suppressed D^+ decay modes with anomalously high branching ratios which are not simply explained by any model. All standard model diagrams that can contribute to these decays are related by symmetries to diagrams for other decays that do not show any such enhancement. If these high branching ratios are confirmed by more precise experiments, they may require new physics to explain them. Anomalies in D_s decays and tests for possible violation of G-parity are discussed.

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1 Two anomalously enhanced D^+ decays to strange meson pairs

Two Cabibbo suppressed D^+ decay modes have anomalously high branching ratios[1]:

$$BR[D^+ \rightarrow K^*(892)^+ \bar{K}^0] = 3.2 \pm 1.5\% \quad (1)$$

$$BR[D^+ \rightarrow K^*(892)^+ \bar{K}^{*0}(892)^0] = 2.6 \pm 1.1\% \quad (2)$$

These are the same order as their corresponding Cabibbo allowed branching ratios

$$BR[D^+ \rightarrow \rho^+ \bar{K}^0] = 6.6 \pm 2.5\% \quad (3)$$

$$BR[D^+ \rightarrow \rho^+ \bar{K}^{*0}(892)^0] = 2.1 \pm 1.3\% \quad (4)$$

In this letter we show that the high branching ratios for these Cabibbo suppressed D^+ decay modes are not simply explained by any model; specifically, all standard model diagrams that can contribute to these decays are related by symmetries to diagrams for other decays that do not show any such enhancement. If these high branching ratios are confirmed by more precise experiments, they may require new physics to explain them.

We first note that the dominant tree diagrams for the corresponding allowed and suppressed decays differ only in the weak vertices $c \rightarrow W^+ + s \rightarrow \rho^+ + s$ and $c \rightarrow W^+ + s \rightarrow K^*(892)^+ + s$: the hadronization of the strange quark s and spectator \bar{d} is common to both decays. These diagrams should show the expected Cabibbo suppression which is not observed.

The possibility that $W^+ \rightarrow K^*(892)^+$ is somehow similar in strength to $W^+ \rightarrow \rho^+$ can be discounted. First, the topologically similar tau decays $BR[\tau^+ \rightarrow K^*(892)^+ \nu] \sim 1.3\%$ and $BR[\tau^+ \rightarrow \rho^+ \nu] \sim 25\%$ exhibit the expected suppression of the former, as do the corresponding D^0 decays

$$BR[D^0 \rightarrow K^*(892)^+ \bar{K}^-] = 0.35 \pm 0.08\% \quad (5)$$

$$BR[D^0 \rightarrow \rho^+ \bar{K}^-] = 10.8 \pm 0.9\%. \quad (6)$$

Indeed, any model of D^+ where the charm quark decays as $c \rightarrow K^{*+} s$ with the s and the spectator \bar{d} combining to make $K^{*+} \bar{K}^0$ and $K^{*+} \bar{K}^{*0}$, will also say that for the D^0 the charmed quark decays as $c \rightarrow K^{*+} s$ and the s and the spectator \bar{u} combine to make $K^{*+} K^-$ and $K^{*+} K^{*-}$. However, the corresponding charged and neutral decays are empirically very different. This is independent of the particular model used for the charmed quark decay.

Thus we need something to explain why changing the spectator makes a big difference.

The above remarks focussed on the dominant tree diagrams. More generally we now note that when we consider all diagrams contributing to the anomalously enhanced decays (1-2), each diagram is related by symmetries to a very similar diagram for one of the following decay modes which show the expected Cabibbo suppression

$$BR[D^+ \rightarrow K^+ \bar{K}^*(892)^0] = 0.42 \pm 0.05\% \quad (7)$$

$$BR[D^0 \rightarrow K^*(892)^+ K^-] = 0.35 \pm 0.08\% \quad (8)$$

$$BR[D^0 \rightarrow K^*(892)^- K^+] = 0.18 \pm 0.01\% \quad (9)$$

$$BR[D^0 \rightarrow K^*(892)^0 \bar{K}^0] < 0.08\% \quad (10)$$

$$BR[D^0 \rightarrow \bar{K}^*(892)^0 K^0] < 0.16\% \quad (11)$$

$$BR[D^0 \rightarrow K^*(892)^0 \bar{K}^*(892)^0] = 0.14 \pm 0.05\% \quad (12)$$

Our conclusion will be that there is no simple diagram that enhances the suppressed modes (1-2) without also enhancing others that show no experimental enhancement.

2 Analysis of contributing diagrams and comparison with related decays

The diagrams contributing to the D^+ decays (1-2) can be classified into two types:

1. Those in which the spectator antiquark \bar{d} appears in the final state and is connected topologically on the same quark line as the initial \bar{d} ; e.g. the tree diagram and the penguin. Diagrams of this type are shown in Figs. 1 and 2.
2. Those in which the spectator antiquark is annihilated and then recreated in a weak annihilation vertex. If no gluons are created from the initial state before the weak vertex, these diagrams go via an intermediate $u\bar{d}$ state which is an eigenstate of G-parity if it has the spin and parity 0^- needed to produce the $K^*(892)^+ \bar{K}^0$ final state. Diagrams of this type are shown in Figs. 3 and 4.

We now examine these in turn.

Diagrams of type 1 for D^+ decay - see Figs. 1 and 2:

These can go into the $K^*(892)^+ K^-$ and $K^*(892)^+ \bar{K}^*(892)^-$ decays of the D^0 by flipping the isospin of the spectator \bar{d} antiquark into a \bar{u} . Since all interactions of the spectator antiquark in the diagram involve only isoscalar gluons, except for the case of the electroweak penguin, the two diagrams have the same contribution.

These diagrams cannot produce an enhancement of the D^+ decay without giving a similar enhancement of the related D^0 decays.

There are two caveats here. One is the electroweak penguin. Since the photon couples more strongly to a spectator \bar{u} than to a spectator \bar{d} it is difficult to see how such a diagram can enhance the D^+ decay relative to the D^0 decay. Furthermore, replacing \bar{d} by \bar{s} would give as the nearest analogue for this electroweak penguin the decays $D_s \rightarrow K^{*+}\phi$ and $D_s \rightarrow K^{*+}\eta_s$. There are no observations of modes containing either one or three K that could be consistent with either of these, which suggests that they are not enhanced. The other caveat is the presence of additional diagrams in the neutral D^0 decays which have no counterpart in the charged decays; we must consider the possibility that the tree diagrams for D^0 are enhanced but that these extra diagrams might reduce or cancel the contribution of the enhanced diagrams. This possibility is discussed later.

Diagrams of type 2 for D^+ decays - see Figs. 3 and 4:

If no gluons are emitted from the initial state, these produce a $u\bar{d}$ state (such as the $\pi(1800)[3]$) which decays conserving G-parity. As the $K^*(892)^+\bar{K}^0$ and $K^+\bar{K}^*(892)^0$ states are G-conjugates of one another, the G-parity eigenstates are $\frac{1}{\sqrt{2}}[K^*(892)^+\bar{K}^0 \pm K^+\bar{K}^*(892)^0]$ and hence a state of a given G-parity will contribute equally to the $K^*(892)^+\bar{K}^0$ and $K^+\bar{K}^*(892)^0$ states. However, the observed branching ratios (eqs. 1 and 7) differ by almost an order of magnitude. Although the presence of diagrams with initial gluons can produce states of opposite G-parity, the two types of diagrams must be fine tuned so that they nearly cancel for the $K^+\bar{K}^*(892)^0$ states and strongly enhance the $K^*(892)^+\bar{K}^0$. This seems highly unlikely. This possibility could be eliminated by precision data on D_s decays where the Cabibbo dominant modes

$$BR[D_s \rightarrow K^{*+}\bar{K}^0] = 4.3 \pm 1.4\%; BR[D_s \rightarrow K^+\bar{K}^{*0}] = 3.3 \pm 0.9\%; \quad (13)$$

are consistent with being the same. There is however the possibility of producing these modes by the color-suppressed topology and a final assessment requires careful determination of the relative importance of these decay mechanisms. There are, however problems with D_s decays that defy conventional explanations and may also indicate the presence of new physics contributions[4]. We discuss these later.

So there seems to be no simple way to explain the large enhancement of these D^+ decays without also implying enhancements for other modes that do not exhibit such effects empirically. If the experimental enhancement holds up this may be a key to new physics.

3 Effects of D^o final state interactions

We now examine possible effects of flavor-changing final state interactions that exist for the D^o decays but not for the D^+ , in order to eliminate the possibility that tree diagrams are enhanced for D^o but are being suppressed by destructive interference with these extra diagrams.

Flipping the isospin of the spectator antiquark in a diagram of type 1 for D^+ decay produces a diagram for D^o decay containing a $u\bar{u}$ pair. The $u\bar{u}$ can be annihilated and changed into a $d\bar{d}$ or $s\bar{s}$ by a final state interaction, which has no counterpart in the diagrams for D^+ decay. To take this into account we first note that the diagram for D^o decay obtained by flipping the isospin of the spectator quark is a mixture of isospins $I = 1$ and $I = 0$.

Thus, while $D^+ \rightarrow \pi^+(1800)[3]$, the D^o could couple via $\pi^0(1800)$ and $\eta(1760)$ say[1]. It is then a priori possible that the combination led to a reduction of the charged kaons and an enhancement of their neutral counterparts (or vice versa). The following isospin sum rule relates the amplitudes for the decay diagrams of type 1, denoted by A_s , to the physical final states and those to the isospin eigenstates:

$$\begin{aligned} & |A_s[D^o \rightarrow K^*(892)^+ K^-]|^2 + |A_s[D^o \rightarrow K^*(892)^o \bar{K}^o]|^2 = \\ & = |A_s[D^o \rightarrow \{K^*(892)\bar{K}\}_{I=0}]|^2 + |A_s[D^o \rightarrow \{K^*(892)\bar{K}\}_{I=1}]|^2 \end{aligned} \quad (14)$$

and analogously for the $K^* \bar{K}^*$ modes.

We now note that the final state in the D^+ decay is a pure isospin eigenstate with $I = 1$. The final state interactions for the $I = 1$ states in the two decays must be the same since the strong final state interactions are isospin invariant. Thus isospin relates the $I = 1$ amplitudes for D^+ and D^o decays

$$A_s[D^o \rightarrow \{K^*(892)\bar{K}\}_{I=1}]^2 = (1/2) \cdot |A_s[D^+ \rightarrow K^*(892)^+ \bar{K}^o]|^2 \quad (15)$$

and so

$$\begin{aligned} & |A_s[D^o \rightarrow K^*(892)^+ K^-]|^2 + |A_s[D^o \rightarrow K^*(892)^o \bar{K}^o]|^2 \kappa \\ & = |A_s[D^o \rightarrow \{K^*(892)\bar{K}\}_{I=0}]|^2 + (1/2) \cdot |A_s[D^+ \rightarrow K^*(892)^+ \bar{K}^o]|^2 \\ & \geq (1/2) \cdot |A_s[D^+ \rightarrow K^*(892)^+ \bar{K}^o]|^2 \end{aligned} \quad (16)$$

Upon allowing for the different life times, this can be rewritten

$$\begin{aligned} & BR[D^o \rightarrow K^*(892)^+ K^-] + BR[D^o \rightarrow K^*(892)^o \bar{K}^o] \\ & \geq (1/2) \cdot BR[D^+ \rightarrow K^*(892)^+ \bar{K}^o] \frac{\tau(D^+)}{\tau(D^o)} \end{aligned} \quad (17)$$

The left hand side is $< 0.6\%$ while the right hand side is $4 \pm 2\%$. Thus it seems that we can rule out the fine tuning conspiracy for the $\bar{K}K^*$ decays at least.

A similar analysis can be applied to the $K^*\bar{K}^*$ decays. Here there is no datum for $BR[D^o \rightarrow K^*(892)^+\bar{K}^*(892)^-]$ and so one cannot definitively rule out such a conspiracy. To satisfy the inequality would require $BR[D^o \rightarrow K^*(892)^+\bar{K}^*(892)^-] \geq 3.1 \pm 1.7\%$. Given that the neutral modes have[1] $BR[D^o \rightarrow K^*(892)^o\bar{K}^*(892)^o] = 0.14 \pm 0.05\%$, such a large branching ratio would be quite startling.

We do not consider here additional diagrams arising from the singly-suppressed c -quark decay $c \rightarrow d\bar{u}d$ which can contribute to D^o and not to D^+ decays via final state interactions creating an $s\bar{s}$ pair. A highly unreasonable conspiracy with fine tuning would be needed to produce a cancellation of the anomalously large diagram of type 1.

It is therefore of interest to check the branching ratios for the transitions (1-2) and reduce the errors. Using the present data we find:

$$BR[D^+ \rightarrow K^*(892)^+\bar{K}^o] + BR[D^+ \rightarrow K^*(892)^+\bar{K}^*(892)^o] = 5.8 \pm 1.9\% \quad (18)$$

This is still large at three standard deviations. Established physics seems only able to explain these data by appeal to fine tuning, which may already be eliminated by other data.

The present data on these anomalous rates come from single experiments [5, 6]. If subsequent experiments show these large branching ratios to be in error, then one may need to reconsider the other branching ratios extracted from the same analyses, (in particular the $D^o \rightarrow K^+K^-$ which also appears to be rather larger than expected[1]: compared with the $D^o \rightarrow \pi^+\pi^-$). Conversely, if the large branching ratios are confirmed with smaller errors, there may be good reason to look for a new physics explanation. Thus we urge high statistics study of these decays in dedicated charm production experiments, such as may be feasible at CLEO-c, Fermilab or GSI.

4 D_s decay puzzles, annihilation and G-parity tests

We now recall some unresolved puzzles in D_s decays[4]. These may require new physics contributions related to those required by the anomalously enhanced singly forbidden decays discussed above.

The D_s decay modes $D_s \rightarrow VP$ and VV show no significant suppression of “color-suppressed” KK^* and K^*K^* relative to “color-favoured” $\phi\pi$ and $\phi\rho$. Contrast this with D^o decays: the D^o and D_s differ only by spectator quark flavor, but definite color suppression is seen in VP and VV D^o decays and not in D_s . How can changing

the flavor of a spectator quark drastically change the degree of color suppression in tree diagrams where the spectator quark does not play an active role?

The simplest explanation would be that these D_s decays are driven by annihilation. If this is the case, then it adds weight to our argument at eq. (13). Establishing the pattern and strengths of the annihilation modes is another critical piece in solving these enigmas.

The observation of the purely leptonic annihilation decay $D_s \rightarrow W^+ \rightarrow \mu^+ \nu_\mu$ implies the existence of the hadronic annihilation without gluons $D_s \rightarrow W^+ \rightarrow u\bar{d} \rightarrow (2n+1)\pi$ where the G parity of a J=0 $u\bar{d}$ state without additional gluons forbids the decay into an even number of pions.

We have assumed that G-parity is a good quantum number in our analysis. It is in principle possible that this is a weak link. It is therefore of interest to look for:

a. The forbidden $D_s \rightarrow 2n\pi$ decays. Even upper limits are of interest. Definite evidence would indicate some contribution other than the simple annihilation. Note that this goes beyond the search for the forbidden $\omega\pi$ mode. Any state which ends up as an even number of pions is forbidden and its observation gives information about the existence of other annihilation-type diagrams including gluons or final-state rescattering.

b. The allowed D_s decays into states containing an odd number of pions. These decays must be there somewhere to be consistent with the observed leptonic decay.

c. Decays into states with several neutral pions may be difficult to detect. States with a single neutral pion can come from allowed odd-G decays into an η and an even number of charged pions. Thus it might be useful to examine all multipion decays with no more than one neutral and classify them as follows:

- (i) All D_s decays into an odd number of charged pions and nothing else.
- (ii) All D_s decays into an odd number of charged pions and an η .
- (iii) All D_s decays where no η is present into an odd number of charged pions and a single π^0 .

The relative numbers of these three inclusive final states might give information on the validity of the G-parity selection rule that we have assumed in our analysis.

There are hints of anomalies already, especially in the $D_s \rightarrow \eta\rho$ and $\eta'\rho$ modes.

The $\eta'\rho/\eta\rho$ ratio = 0.9 ± 0.3 appears to be anomalously large if it is due to a spectator tree diagram, where the p-wave phase space should favour the η significantly and the amplitude ratio is of order unity with a value depending in the mixing angle, For example, we note that

$$\begin{aligned} BR(D_s \rightarrow \eta l^+ \nu) &= 3.5 \pm 0.07\% \\ BR(D_s \rightarrow \eta' l^+ \nu) &= 0.88 \pm 0.03\%. \end{aligned} \tag{19}$$

However, there is no clear indication of the nature of the additional contribution needed. Standard model physics implies that different parities and G-parities are not mixed by final state interactions. Positive G-parity is exotic for both parities and cannot have contributions that go via an intermediate state of a single quark-antiquark pair. The $\rho\eta$ and $\rho\eta'$ channels are exotic while $\pi\eta$ and $\pi\eta'$ are not. Yet all states seem to have anomalously large branching ratios and favor the η' . There seems to be a common mechanism independent of the quantum number of the final state. The required additional contribution cannot be a simple annihilation without additional gluons emitted before annihilation since this produces a G-parity eigenstate which is right for $\eta'\pi$, but wrong for $\eta'\rho$.

Annihilation with at least two gluons emitted from the initial state and interaction between these gluons and the $u\bar{d}$ state produced by an annihilation diagram could give a small amplitude which might interfere constructively with the η' amplitudes and destructively with η . This diagram must also show up in other G-forbidden even- π amplitudes. Stringent upper limits on this diagram would exclude this mechanism.

Annihilation with two gluons emitted from the initial state which then turn into an η' via a hairpin diagram will produce the η' rather than the η . This mechanism can be compared with $J/\psi \rightarrow \eta'\gamma$ which is also dominated by a two-gluon hairpin diagram. However, one would also expect to see this diagram in the semileptonic decay $D_s \rightarrow \eta'\mu^+\nu_\mu$, in contradiction to data where the η'/η ratio does not seem to be enhanced.

In summary, we advocate a systematic study of Cabibbo suppressed D decays and of specific D_s channels to test the validity of G-parity and other generally accepted selection rules in the heavy flavor sector.

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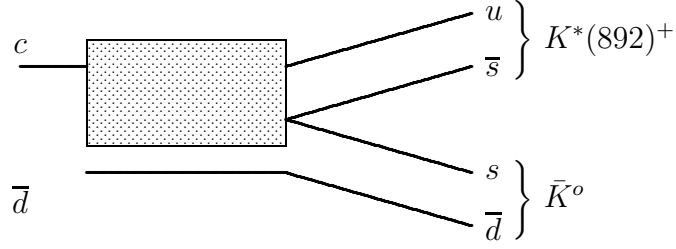


Figure 1:
Cabibbo suppressed inactive spectator diagram

$$BR[D^+ \rightarrow K^*(892)^+ \bar{K}^0] = 3.2 \pm 1.5\%$$

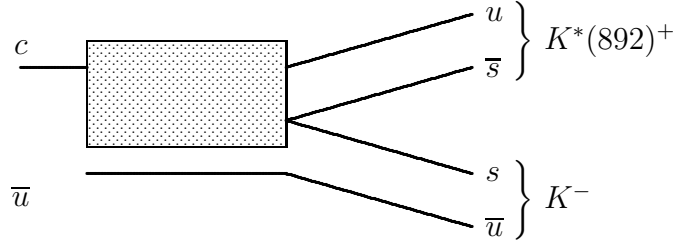


Figure 2:
Cabibbo suppressed inactive spectator diagram

$$BR[D^0 \rightarrow K^*(892)^+ K^-] = 0.35 \pm 0.08\%$$

The two diagrams differ only by isospin flip of spectator quark

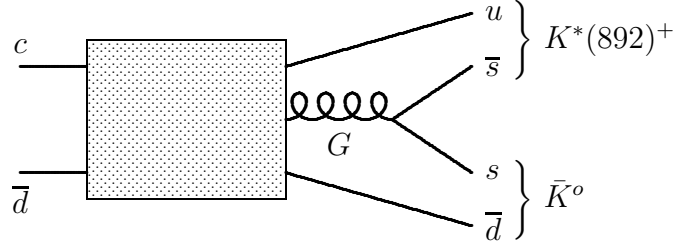


Figure 3:
Annihilation Diagram. G denotes any number of gluons.

$$BR[D^+ \rightarrow K^*(892)^+ \bar{K}^0] = 3.2 \pm 1.5\%$$

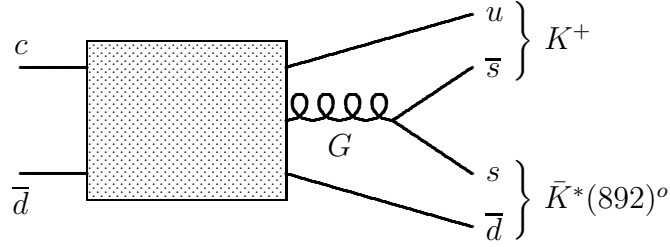


Figure 4:
Annihilation Diagram. G denotes any number of gluons.

$$BR[D^+ \rightarrow K^+ \bar{K}^*(892)^0] = 0.42 \pm 0.05\%$$

Two final states are G -conjugate

Any G -conserving strong interaction must fine-tune
 G -even and G -odd amplitudes to interfere
constructively for $D^+ \rightarrow K^*(892)^+ \bar{K}^0$
destructively for $D^+ \rightarrow K^+ \bar{K}^*(892)^0$

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